The Scottish Lochs and their Origin.

By Professor J. W. GREGORY, D.Sc., F.R.S., being a communication from the Geographical Section.

[Read before the Society, 25th February, 1914].

THE Scottish lochs may be divided topographically into two groups —one consisting of arms of the seas and the other of fresh water lakes. Both groups occupy basins of essentially the same character, and the difference between the groups is only due to the accident of level. They pass gradually into one another according as the seaward rim of the basin happens to be a few feet above or below sea level; for example, Loch Lomond is now a fresh water lake and it was once an arm of the sea. A more important classification of these lochs is based on the difference in character of their valleys; and in this respect the Scottish lochs and estuaries may be divided into three types, rias or firths, fiords, and fiards.

Rias are ordinary estuaries, they are drowned land valleys, and are bounded by rounded slopes and curved lines; they expand seaward both in width and depth, and the sea outside is deeper than it is within. Bantry Bay in southern Ireland and the Firths of Tay and Forth are examples of such estuaries. They are known as rias, after those of Galicia in north-western Spain.

The term fiord is Norwegian in origin and is used in Norway for any arm of the sea; but it has now been accepted in geography for long narrow arms of the sea which have high steep opposing walls, and which turn and receive their tributaries at sharp, regular angles.

The term fiard is the Swedish form of fiord; and the typical fiards are those on the south-eastern coast of Sweden. They are bounded by gentle slopes; their margins are very sinuous, extending out in many fretted promontories and peninsulas; numerous low islands, also with very indented outlines, often occur along their shores.

The differences between fiords and fiards is due to the height of the adjacent land. Fiords occur in highlands and fiards in lowlands. The two types look very different on maps, but they are intimately connected in origin. They are both valleys which have been drowned, and the difference between them depends on the depth of the submergence. If the water lies low on the valley walls, the sides are parallel and straight, and the inlet is a fiord. If the water level has risen to the upper parts of the slopes where denudation has acted longest and been most effective, then the shore line is very sinuous, for it follows the curving contours up the valleys and the ridges project in indented promontories, peninsulas and islets. The arm of the sea is then a fiard.

Many Scottish lochs like Loch Long, Loch Sunart, Loch Hourn are true fiords. Loch Ericht and upper Loch Lomond represent the same type among the fresh water lochs; and Lochinver, Loch Linnhe, Loch Sween, Loch Killisport and other lochs in south-western Argyll are Scottish fiards. Loch Rannoch is a fresh water representative of the fiard type.

The fiords are the more instructive group. Many fiards are only worn down fiords, and others are fiords so deeply drowned that most of the fiord valley is invisible.

The Scottish fiord-like lochs are typical fiords. They have trough shaped valleys and steep parallel walls, and flat floors; many of them are very deep, their floors sinking hundreds of feet beneath sea level; and they occur in a dissected plateau composed of old rocks; and they are arranged in a network of intersecting lines.

The problem presented by these lochs is how to explain the origin of these angular networks of narrow, straight-sided, parallel-walled valleys, and of their deep basins, which are often almost separated from the sea by a shallow threshold, or wholly separated by a tract of land.

The simplest and for long the most popular explanation is that these loch basins were excavated by ice. The arguments for this hypothesis are that only ice could excavate such deep rock basins, that only ice could convert ordinary sinuous river valleys into straight parallel-sided trough-valleys, that the action of ice along these valleys is shown by abundant evidence, and that fiords only occur in glaciated areas.

In a recent book, "The Nature and Origin of Fiords," I have

tried to refute this theory by showing that fiords, trough valleys, and deep basins are formed by various agencies, that they sometimes occur in countries which have never been glaciated, that where the fiords and loch basins occur in countries that have been glaciated the valleys were there before the ice, that the action of ice is to destroy fiords and not to make them, and that in some countries, as in Alaska, the coasts that have been glaciated may have no fiords, while there are fiords on unglaciated parts of the coast.

It is therefore necessary to look for some other explanation of fiords. They appear to be due to earth movements, and are the result of rifts due to the tearing apart of areas of hard rock during uplift; this rifting is sometimes combined with faulting and the subsidence of strips of land forming rift-valleys. The rifts are enlarged by the ordinary agents of denudation.

Loch Morar.

The most critical test for any hypothesis of the origin of the Scottish loch basins is its application to Loch Morar. It is the most difficult loch basin to explain because it is the deepest. The level of the loch above the sea according to Murray and Pullar's Loch Survey is 30½ feet, and according to the Ordnance Survey of 1869 is was then 30·6 feet. The greatest depth is 1017 feet, so that the bed of the lake descends about 987 feet below sea level. The existence of this great deep is all the more remarkable since the same depth is not reached by the sea-floor around Scotland until its descent to the North Atlantic basin beyond the Outer Hebrides.

The loch is unquestionably a rock basin. There are abundant exposures of bed rock on its shores, and the outlet through the Morar River is mainly across rock. The loch basin is therefore not a river valley that has been blocked by moraines.

The theory that the basin has been excavated by ice erosion is recommended by its simplicity, by the fact that the country was once all covered by ice, and by the difficulty otherwise of explaining so deep a hollow.

Loch Morar, however, has not the main peculiarity in shape which especially recommended the glacial origin of many lake basins. They are often, e.g., Loch Lomond, shovel-

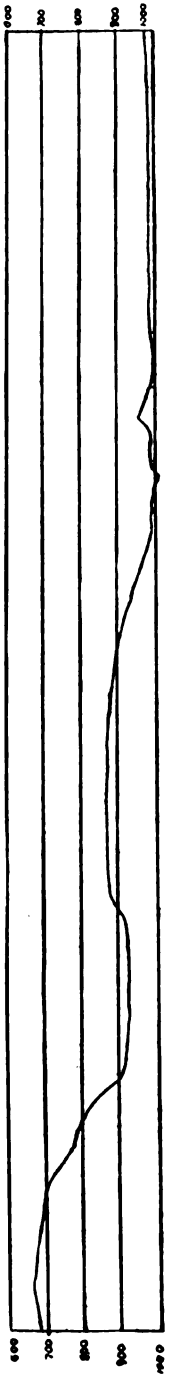

FIG. 1.—SECTION ALONG THE DEEPEST PART OF LOCH MORAR (after Murray & Pullar's Loch Survey).

shaped, or deepest at the inner end. In Loch Morar the deepest point is at the middle, and the slopes on both sides down to it are long and gradual. In other respects also Loch Morar is not in a very favourable position for the glacial hypothesis. There seems no special reason why glaciers should have excavated so deep a depression along this line. The surrounding country does not appear particularly favourable to either the great accumulation of ice or to especially active erosion. There is less high land in the neighbourhood of the loch than in adjoining districts, such as Ben Nevis (4406 feet) to the east-south-east, or the Mam Soul (3862 feet) and Ben Attow (3383 feet) mass to the north-east. Three peaks rise to 3133 feet, 3164 feet, and 3148 feet on a ridge to the south of the Glen Pean valley, which leads from Loch Morar to Loch Arkaig, but the amount of land near Loch Morar above 2000 feet is comparatively small. The high land, moreover, owing to its distance inland, would appear to be in less favourable positions for collecting great snowfall than the mountains of Skye and Mull. There seems no reason why an especially powerful ice stream should have flowed down Loch Morar; and according to Sir Archibald Geikie's map of the glaciation of Scotland (Scenery of Scotland, 3rd edition, 1901, pl. iv.) the ice from the mountains to the east of Loch Morar passed south-eastward to Loch Ailort, and according to his map Loch Morar was not on one of the main lines of ice flow.

From study of the available maps three suggestions occurred to me as possible explanations of the formation of Loch Morar by glacial action:—

(1) The loch might have been worn out along a line of soft rock.

(2) The excavation might have been greatest at this deep hollow owing to the speed of the ice and its corroding power having been increased in consequence of the junction of a great tributary glacier from Glen Meoble.

(3) An especially active group of subglacial pot holes might have been long at work there.

On a visit to Lake Morar last autumn I failed to find evidence for any of these possibilities. The general strike of the rocks in this district is from between north and north-west to between south and south-east; the grain of the country is oblique to the loch basin, which cannot therefore be due to the removal of some easily weathered band in the gneisses. The basic dykes in this district run from north-west to south-east, and I could see no sign of any dyke at the western end of the loch such as would serve to account for the formation of this long straight trough.

Mr E. C. Andrews has suggested that the excavating powers of glaciers vary with their velocity, so that a glacier corrodes its bed most deeply where its channel is narrow and loses power when its valley becomes wide. Loch Lomond might be cited in agreement with this principle; and as the 1017 feet hollow on the bed of Loch Morar is situated nearly opposite the junction of the ice from Glen Meoble, it might be attributed to the increased ice pressure there. The ice was, however, probably reduced there by overflow from Loch Morar into Tarbet Bay on Loch Nevis. It might be suggested that ice from Loch Nevis overflowed into Loch Morar, but the evidence of the glaciation of the slopes of Cnoc a Bhac Fhalaichte shows that the movement at the Tarbet Gap was from Loch Morar northward into Loch Nevis.

The suggestion that the great depression was formed by pot-hole action owing to a series of crevasses having been kept open above that place is untenable, since the depression is reached by a long gradual slope downward and is not a sudden local deepening, except for a small area on the lowest floor.

A study of the maps of the district gave no satisfactory explanation of this hollow. They show that the northern shore opposite the deepest part is irregular; but the numerous projections

from the shore might have been due to recent alluvium or moraines. These islets and promontories, however, consist of bare rugged rocks. Some of the projections are narrow bars of rock which ice erosion would easily have planed away. If a glacier had hollowed the loch basin then, at the beginning of its work, the ice must have pressed heavily against the present shores; and ice under such conditions planes away the rocky projections into a smooth even wall.

It is on the sides of valleys that glaciers are universally admitted to have their greatest power of wearing away rocks. Rivers generally form sinuous valleys, whereas ice, owing to its more sluggish flow, presses heavily against the spurs on the sides of a valley and wears them away. This flattening of the walls by spur truncation may be well seen, for example, in Glen Nevis, and this process has given many Scottish glens their characteristic form. The triangular facets produced by the truncation of the spurs is another characteristic feature produced by the same process. If the ice opposite Swordland had had sufficient excavating power to dig out a basin a thousand feet deep, it should certainly have glaciated and worn down the ridges on the sides of the valley.

The northern shore of Loch Morar, to the west of Swordland and of the Tarbet gap, and opposite the deepest part of the loch, consists of a series of jagged narrow ridges which fall steeply to the loch. The view of these ridges, looking westward from Swordland, is singularly unglaciated in aspect. Between Swordland and the headland east of Brinacory there are six rocky spurs with serrate crests. It is only close to the shore that they show signs of the usual spur truncation by ice. It seems to me absolutely inexplicable, if a glacier had dug out a deep depression 1000 feet deep on the bed of the loch, that it should have left these exposed ridges beside it so strikingly unglaciated. It may be said that they have been left unglaciated because the ice pressure was reduced at this part of the loch by the existence of the deep hollow; but that suggestion would give away the case for the ice erosion of the loch basin by recognising its pre-glacial age. As the ice has been so inefficient on the northern shore of the deepest part of the loch it seems to me inconceivable that it should there have been so active on its bed.

The only alternative to the glacial theory is that the basin of Loch Morar was due to movements which caused a long east and

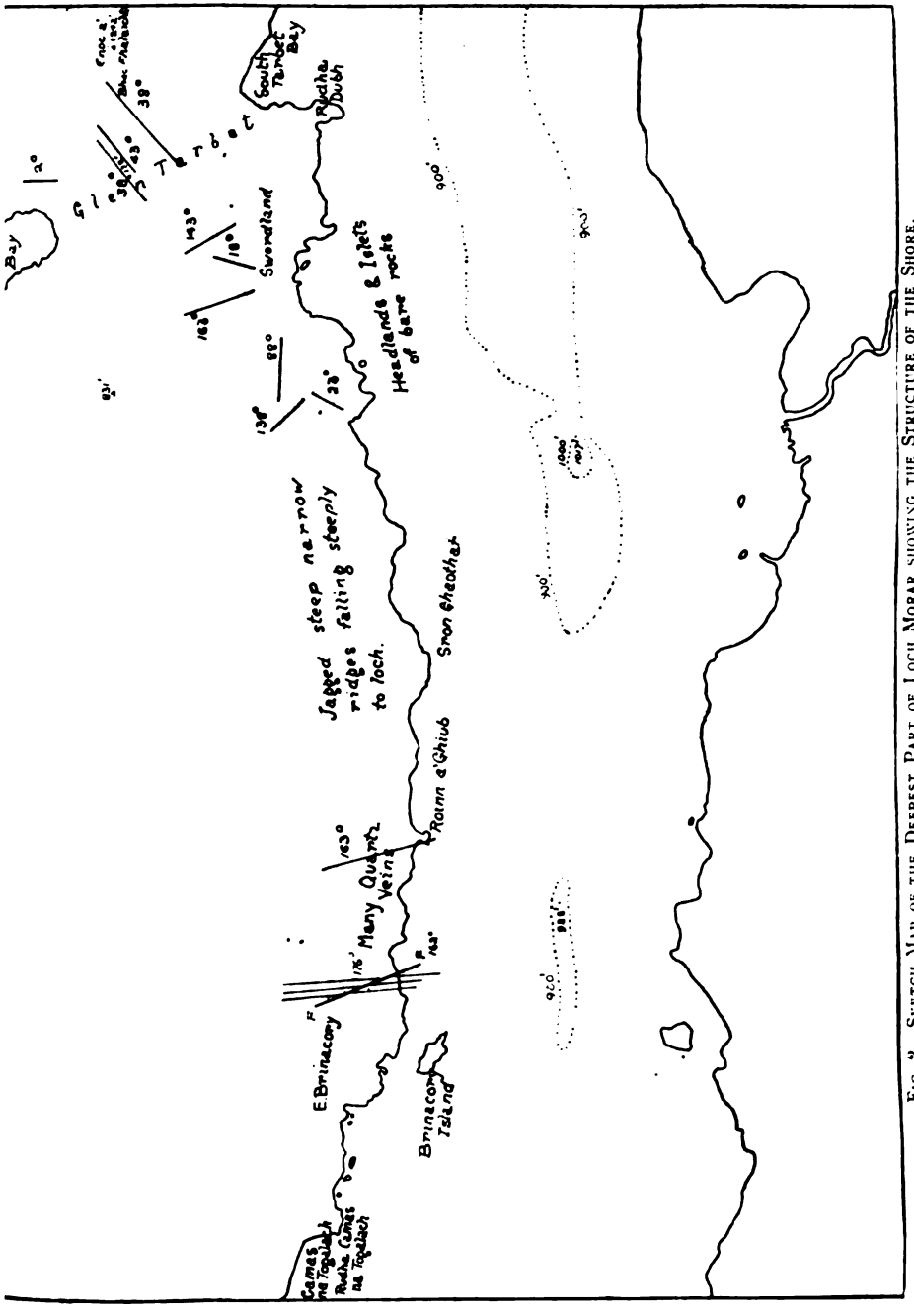

FIG. 2.—SKETCH MAP OF THE DEEPEST PART OF LOCH MORAR SHOWING THE STRUCTURE OF THE SHORE.

west rift. The geology of this area is little known, but a hurried excursion along the northern shore of the loch showed clear evidence of local disturbance of the rocks. The gneiss at the western end of the loch has the normal trend; further east the rocks show many signs of faulting and crushing. From Brinacory eastward abundant quartz veins, some of which occur along well exposed faults, indicate increasing disturbance; and in the area to the north of the greatest depression the strike of the rock is very irregular, as shown on the sketch map, Fig. 2.

The foliation has been often thrown round, so that in places it trends east and west; in the pass from South Tarbet to Tarbet Bay it is in places almost north-easterly to south-westerly.

The contrast between the rugged non-glaciated aspect of the land between Swordland and Brinacory, with the ice worn front of the mountain to the east of Tarbet and with the glaciated slopes to the west of Brinacory, could be most easily explained by unequal movements of the ground since glacial time.

The general geographical relations of Loch Morar appear more easily explained by attributing the loch basin to earth movements than to glacial erosion. Loch Morar is situated on a long east and west valley which is continued further east by Loch Arkaig. This part of Scotland is traversed by three main series of depressions. Fig. 3.

The first series trends east and west; it includes Loch Morar, Loch Garry, Loch Arkaig, Loch Eil, the inner and outer parts of Loch Sunart, the western part of Loch Sheil, Loch Leven and the continuation of its valley eastward to Loch Rannoch, lower Loch Etive and Loch Earn; and in eastern Scotland the Morar-Arkaig line is continued by the valley of the Dee.

The valleys of the second series run from north-east to south-west along the Great Glen and along the various valleys parallel to it, such as the Sound of Sleat, Loch Shiel, the middle part of Loch Sunart, Loch Ericht, the trough shaped depressions on the bed of the Great and Little Minch, which Mackinder has suggested are due to a submarine rift valley; and this series is also parallel to the eastern coast of Scotland from Peterhead to the estuary of the Tay.

The trend of the third series of lochs is from north-west to south-east. This series includes, amongst many others, Loch Broom, the Sound of Mull, the middle part of Loch Nevis just to

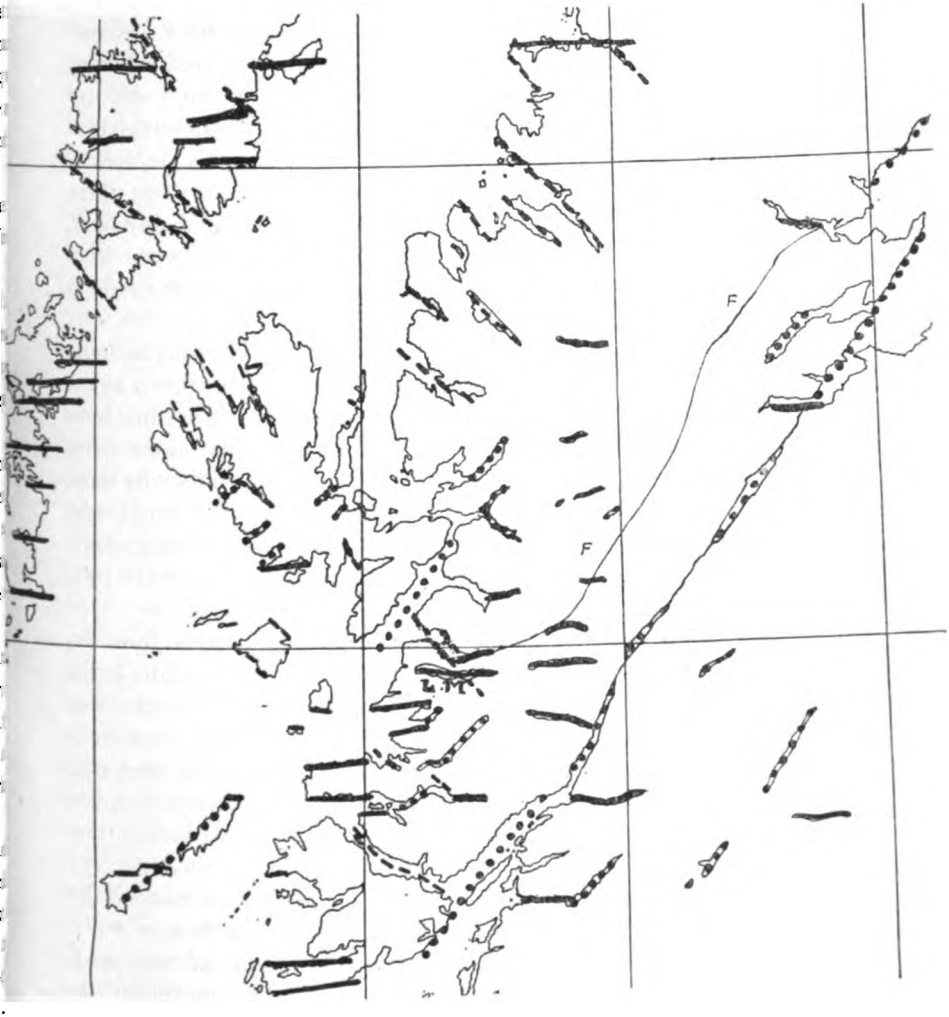

FIG. 3.—THE TECTONIC LINES OF N.W. SCOTLAND.

the north of the Morar deep, and various lochs and coast lines in Skye and the Hebrides.

The deep on Loch Morar occurs at the intersection of these three lines. Sir Archibald Geikie's Geological Map of Scotland shows that the Glen Affric fault, which brings the Old Red Sandstones against the gneisses to the west of Dingwall and traverses the western part of Loch Quoich, lies along the upper end of Loch Nevis; and its continuation across Loch Morar would pass through the great central deep. The existence of this depression may be attributed to the combined influence of these three tectonic lines. The floor of the depression has probably sunk, while at the meeting of the three rift lines the rocks would have been greatly crushed and weakened, and have thus been more easily removed by denudation.

Loch Morar is not exceptional in its association with tectonic lines. Around western Scotland from the Pentland Firth to the Firth of Clyde there are fifty-one chief sea lochs, including both fiords and fiards. There is clear evidence of faulting along forty-two of them. There is evidence of probable faulting in three more. Of the remaining six, of which three are fiards, and regarding three of which I have no information as to their geology, there is no evidence of faulting; but faults may be present in each of these cases.[1]

The ordinary fault movements along these lines were, however, secondary in their action, and not the primary cause of the lochs, which were formed by rifting, not by faulting. On the settlement of the country faulting inevitably occurred, and the new faults naturally followed along older faults and also along the new rifts.

It is the cause of the rifting to which we have to turn to explain the lochs and their valleys. It seems reasonable to believe that these great valleys owe their arrangement to one cause. In middle Kainozoic times north-western Europe was buckled by waves which travelled northward from the disturbances which uplifted the Alps and the Pyrenees. The effects of this movement are shown in the south of England by the folding of the country on east and west lines; the northern limb of one arch survives in the Isle of Wight, and another arch rose across the

[1] A list of the lochs and statement of evidence as to their associated faults is published in the Scottish Geographical Journal, May, 1914.

Weald of Kent. A similar upfold on an east and west line across Scotland from Skye to Aberdeen would have cracked these hard rocks and opened the old joints and faults into east and west rifts across the country; and these rifts would have been crossed by members of another series. Cracks formed by torsion tend to develope along two intersecting series of lines, the angle between which depends on the direction from which the twist comes, and on the grain of the area affected. The lines of stress in a country are doubtless deflected in accordance with its grain.

The greatest line of weakness in central Scotland is along the old faults of the Great Glen and other parallel disturbances. It was therefore natural that one series of rifts should have followed the fractures of the Great Glen, and that the other series should meet the first series at angles varying from right angles to about 60°.

The distribution of the loch lines of Scotland is just what might be expected from a double series of intersecting branch rifts rising from a main series of east and west rifts. The distribution of normal faults is often due to the same cause as controls the distribution of rifts, and in many faulted areas the faults occur in two main series,—a dominant parallel series and secondary faults, usually at angles of between 60° and 90° to the main series; and this is exactly the plan of the Scottish loch valleys.

This arrangement of valleys seems quite inconsistent with their glacial origin. If they had been cut out by ice they should have radiated from the chief centres of ice formation. Yet the major area of ice accumulation in Scotland, Ben Macdhui and the Cairngorm group, has practically no lochs; while Ben Nevis, another important glacial centre, is surrounded by a concentric series of valleys and not a radial series.

The glacial theory, moreover, utterly fails to explain the restriction of the lochs to the western part of the country. The first striking fact in regard to the distribution of lochs observed on examination of a map of Scotland is that both fresh water and sea water lochs are confined to the western half of the country. With a few trivial exceptions the long narrow lakes all lie to the west of the fourth meridian; and the sea lochs are all on the western coast, while the eastern coast has long even shore lines. The most striking contrast in the map of Scotland is that between the straight eastern shores and the western labyrinth of straits

and lochs. The eastern half of Scotland has been as intensely glaciated as the western. I know of no explanation of the absence of lochs from eastern Scotland on the glacial theory; but on the earth movement theory it is natural. It is a world wide arrangement. Fiords are characteristic of western coasts, because they are due to a group of earth movements which uplift the western areas and give the lands a long slope downward to the east.

The nature of the loch valleys as troughs cut across a plateau which has been uplifted in comparatively recent geological times is illustrated by Fig. 4, a section across the eastern Kyle of Bute, kindly drawn by Mr W. R. Smellie. The amount of glacial excavation required to give that loch valley its trough-like form is comparatively small.

That the loch valleys were not excavated by ice is most conclusively demonstrated by the fact that they were pre-glacial. Their direction does not correspond with the main lines of Sir Archibald Geikie's map of Scottish glaciation, which represents the ice as having ridden across the country in directions that were quite independent of the loch valleys and coast lines.

No doubt in the earlier and later stages of the advance of the ice the glaciation would have flowed along any valley that afforded it an easy line of downflow. But when the country was covered by the ice sheet, the main flow was outward from the main centres of snow fall, and the ice overrode the older valleys. Sir Archibald Geikie's map has been confirmed by the detailed study of smaller areas; e.g. Wright and Bailey's map of the glaciation of Colonsay, shows that the ice there overrode the lochs. In the Shetland Isles the ice also flowed across the main geographical lines, and its effect has been to wear away the edges of the valleys; it has thus destroyed the originally fiord-like character of the lochs. The evidence seems convincing that in Scotland, as in other fiord areas, the lochs and loch basins were all pre-glacial.

The glacial hypothesis is at least incomplete, for it does not explain the arrangement of the chief valleys which contain the lochs. Why should ice have worn out four long parallel valleys trending from north-east to south-west across north-western Scotland? The first of these is the line of Loch Fyne, the upper part of which is on the same line as Loch Ericht; the second is the Great Glen which runs from the Moray Firth and continues the long straight north-western shore of that firth through the valley

of Loch Ness, Loch Lochy and Loch Linnhe, and finally deepens seaward to the Firth of Lorn; the third parallel line begins with upper Loch Carron, continues through the Sound of Sleat, and then widens and deepens to the channel between Coll and Tiree on the one side and Mull on the other. The Loch Carron-Sleat line differs from that of the Great Glen as it is at a lower level and has therefore been drowned more extensively by the sea. The fourth line is that of the channel on the floor of the Great and Little Minch, which Mackinder has suggested is a submarine rift-valley. Why should ice erosion have cut out these great trenches, which continue their course independent of the structure of the country and utterly regardless of the conditions that affect the formation of snow and ice; Sir A. Geikie's map of Scottish glaciations shows that the ice flowed across these valleys and not along them. If that map be right the valleys must have been in

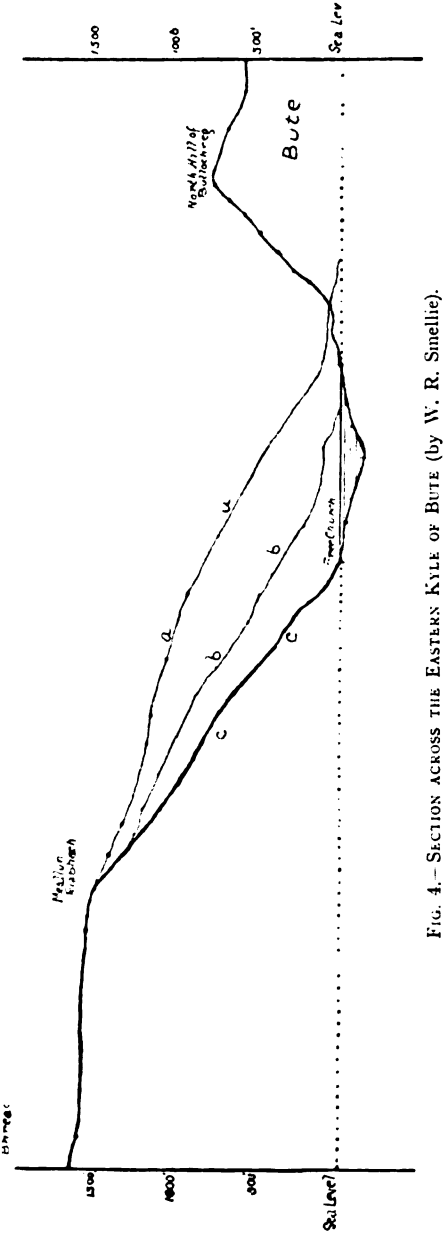

FIG. 4.—SECTION ACROSS THE EASTERN KYLE OF BUTE (by W. R. Snellie).

existence before the glacial period. The glacial theory is in fact only a theory of the alteration of loch valleys and not of their origin.

The plan of the Scottish loch valleys shows that their origin is tectonic. They are arranged in angular networks of intersecting lines. This arrangement is well seen in all typical fiord areas, as in south-western Scandinavia, Greenland, New Zealand, and Patagonia. The distribution of fiord valleys resembles that of cracks in slabs of bent or twisted glass, and is essentially distinct from the convergent plan of river and glacier valleys, in which the tributaries unite like the branches of a tree.

The argument in favour of the glacial origin of fiords which has probably had the greatest influence in its favour is the claim that they only occur in the colder regions of the world. This claim is not wholly true as there are typical fiords in unglaciated regions as in Dalmatia; and if the valleys of Sinai were submerged they would form a typical fiord group.

Nevertheless, despite such exceptions, it is generally true that fiords are characteristic of the colder parts of the world. I have endeavoured in my recent book on fiords to show that this distribution is due to the Polar regions undergoing greater vertical oscillations than the tropical regions. The earth is subject to a panting movement of the Polar regions from which the tropics are free. This conclusion is proved amongst other evidence by the raised beaches which occur around the circumpolar seas and are local and less regular in the tropics. The widespread successive raised beaches, which are well displayed on the coasts of Scotland and Scandinavia, are as characteristically circumpolar as the fiords.

The oscillation of the Polar regions has rifted the areas of hard rock and thus produced the fiords. Hence the Scottish lochs like other fiords are not due to local agents wearing out furrows on an impassive earth. That view explains neither their features nor their distribution. They are the result of the cracking of areas of hard rocks during slow uplifts. These rifts have been subsequently enlarged by denudation and drowned by subsidence beneath the sea. The cause of our Scottish lochs is the rupturing of northern Britain as it uprose on one of the waves which traversed north-western Europe during the great crustal storm that upheaved the Alps.